Title: BSM Theory

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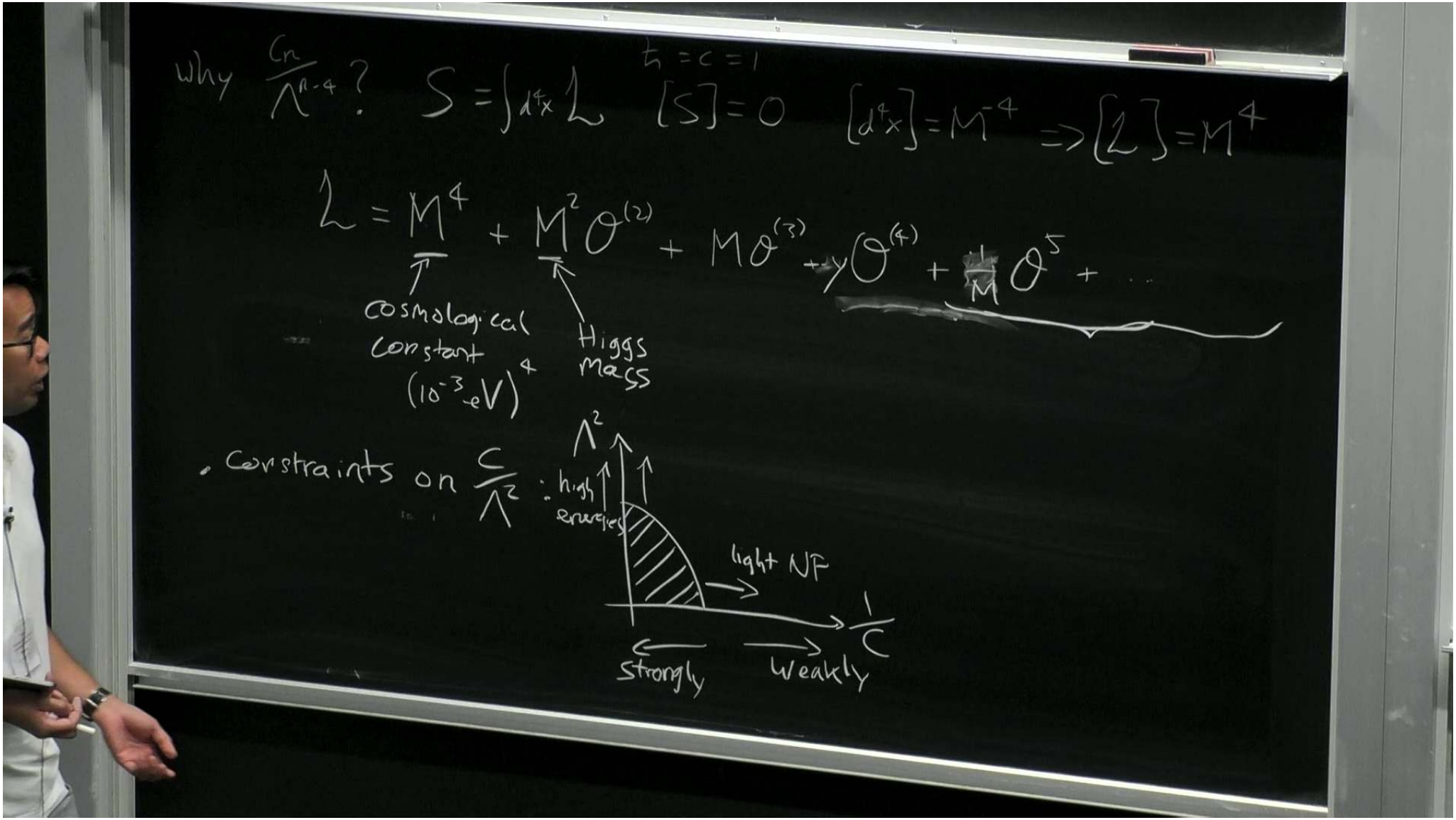
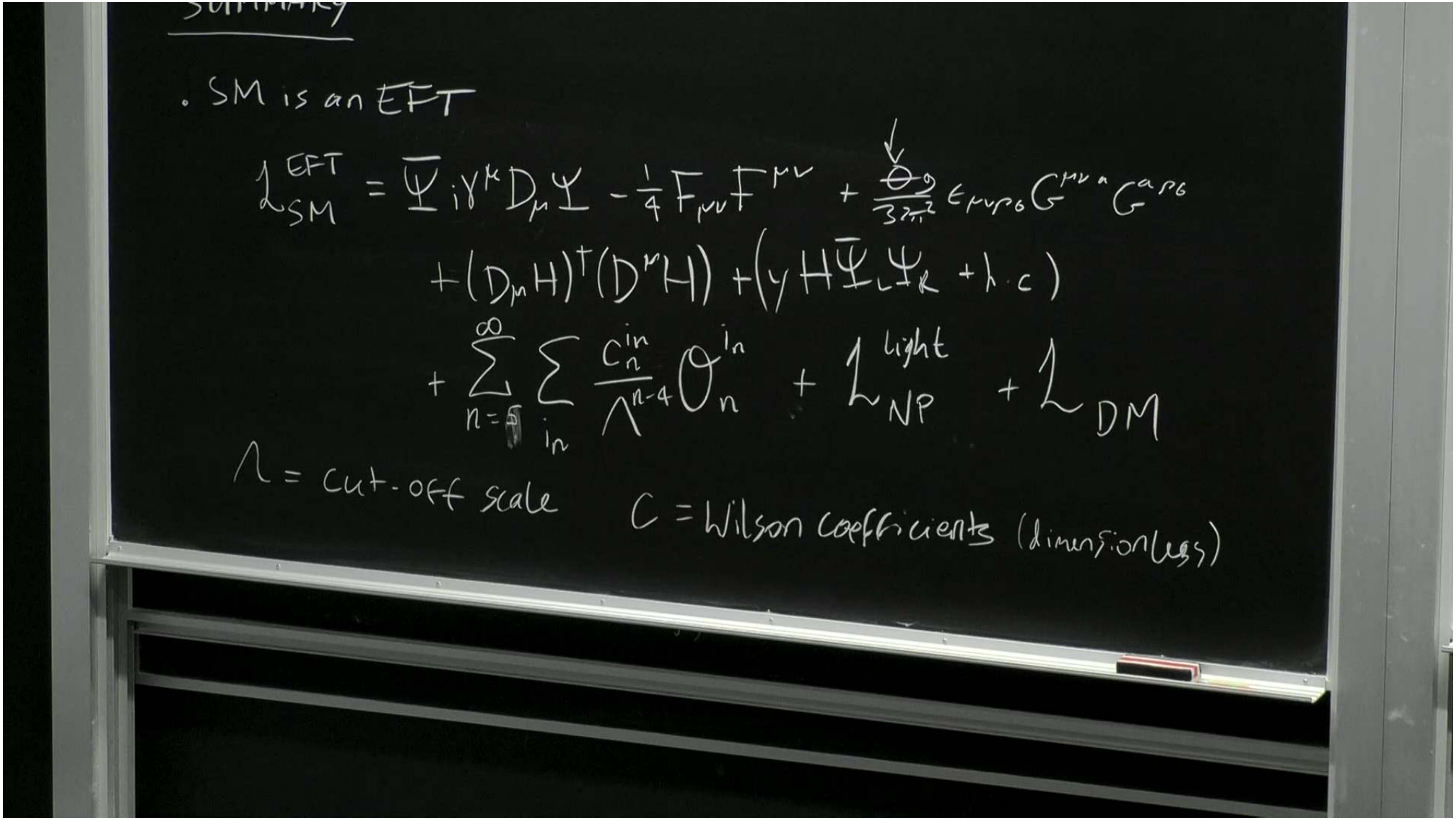
SUMMARY

. SM is an EFT

$$\mathcal{L}_{SM}^{EFT} = \bar{\Psi} i\gamma^\mu D_\mu \Psi - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$
$$+ (D_\mu H)^\dagger (D^\mu H) + \left(y H \bar{\Psi}_L \Psi_R + h.c \right)$$
$$+ \sum_{n=5}^{\infty} \sum_{i_n} \frac{C_n^{i_n}}{\Lambda^{n-4}} O_n^{i_n} + \mathcal{L}_{NP}^{light}$$

Λ = cut-off scale C = Wilson coefficients (dimensionless)


Why $\frac{C_n}{\Lambda^{n-4}}$? $S = \int d^4x \mathcal{L}$ $\hbar = c = 1$ $[S] = 0$ $[d^4x] = M^{-4}$ $\Rightarrow [\mathcal{L}] = M^4$
$\mathcal{L} = M^4 + M^2 O^{(2)} + M O^{(3)} + y O^{(4)} + \frac{1}{M} O^5 + \dots$
cosmological constant $(10^{-3}\,eV)^4$
Higgs mass
• Constraints on $\frac{C}{\Lambda^2}$:
Λ^2
high energies
light NF
$\frac{1}{C}$
strongly
weakly


Summary
. SM is an EFT
$\mathcal{L}_{SM}^{EFT} = \bar{\Psi} i\gamma^\mu D_\mu \Psi - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{\theta g}{32\pi^2} \epsilon_{\mu\nu\rho\sigma} G^{\mu\nu a} G^{a\rho\sigma}$
$+ (D_\mu H)^\dagger (D^\mu H) + (y H \bar{\Psi}_L \Psi_R + h.c.)$
$+ \sum_{n=5}^{\infty} \sum_{i_n} \frac{C_n^{i_n}}{\Lambda^{n-4}} O_n^{i_n} + \mathcal{L}_{NP}^{light} + \mathcal{L}_{DM}$
Λ = cut-off scale
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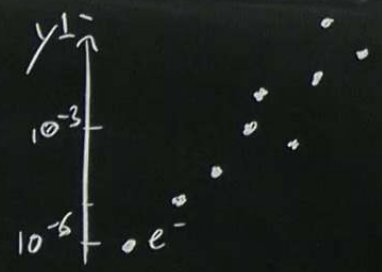
- Problems of the SM
  - Aesthetic: yukawas, flavour structure, put in hand
    Higgs potential is arbitrary
  - Cancellations:



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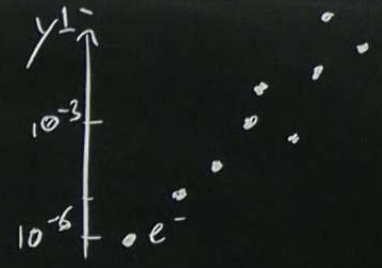
  - Theory breakdown:



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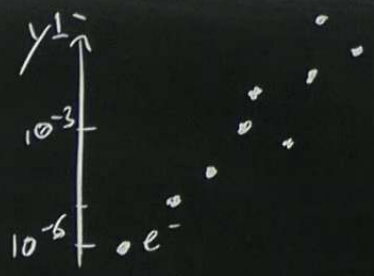

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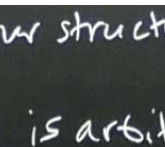
- Science is removing arbitrariness from explanations of natural phenomena



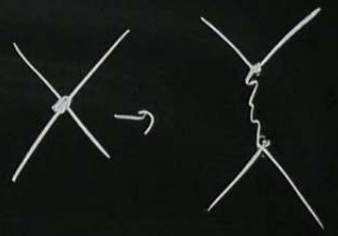
- Principle, not practicality

↑ economy of principles ↑ limitations of technology

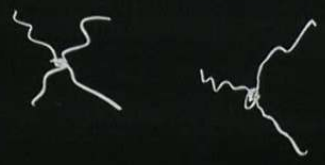
$F = ma$

- m (inertia) $\neq$ equivalence principle
  $\| \quad$ (gravity)
  q

- Fermi theory: universality, V-A, put in hand



- Gauge theories → Single parameter



- Everything about the Higgs is arbitrary: parametrisation c.f. Condensed matter Higgs
- Expect Higgs sector to be calculable in underlying UV theory
- What is the microscopic origin of the Higgs?
- Such a theory has a calculable Higgs mass e.g.
  - Composite Higgs: $V(H) \simeq -\alpha f^2 \sin^2\left(\frac{H}{f}\right) + \beta f^2 \sin^4\left(\frac{H}{f}\right)$

$$m_H^2 = 8\left(\frac{\alpha}{2\beta}\right)\left(1 - \frac{\alpha}{2\beta}\right)\beta$$

$\left\{\ll 1\right.$

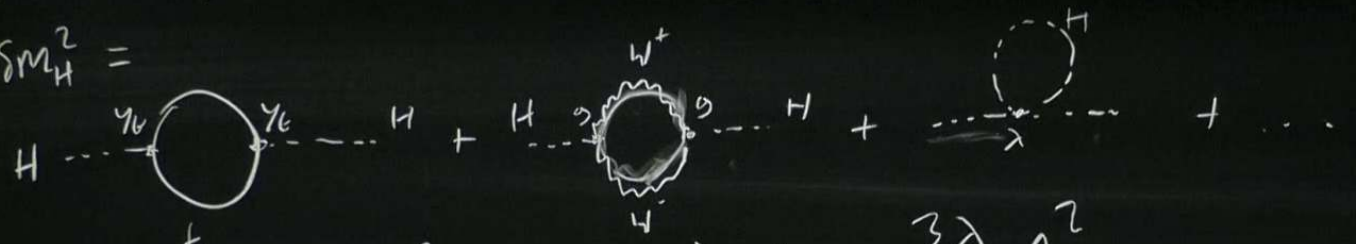
- Supersymmetry: $m_H^2 \sim M_Z^2 \sim (m_{H_u}^2 + |\mu|^2)$

$\mu \lesssim 200$ GeV $\quad m_{\tilde{t}} \lesssim 400$ GeV for 10%

$$\delta m_{H_u}^2(\tilde{t}) = -\frac{3y_t^2}{4\pi^2} m_{\tilde{t}}^2 \log\left(\frac{\Lambda}{m_{\tilde{t}}}\right)$$

- Sensitivity of M_H^2 to Λ^2 is a general consequence of symmetries

- $\delta m_H^2 =$



$$\sim \frac{3y_t^2}{4\pi^2}\Lambda^2 - \frac{3g^2}{8\pi^2}\left(\frac{1}{4}+\frac{1}{8\cos^2\theta_W}\right)\Lambda^2 - \frac{3\lambda}{8\pi^2}\Lambda^2 + \dots$$

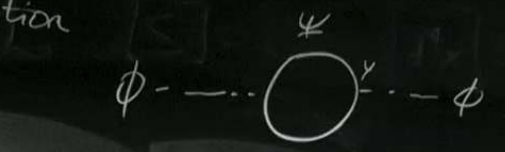
$$\Delta = \frac{\delta m_H^2}{m_H^2} \sim \left(\frac{\Lambda}{450\,\text{GeV}}\right)^2$$

$m_H^{2\,exp} = m_H^{2\,bare} + \delta m_H^2$

↑ in SM Higgs mass is just a independent parameter

$\hbar = c = 1$

- Independent of regularisation
  e.g dim. reg.

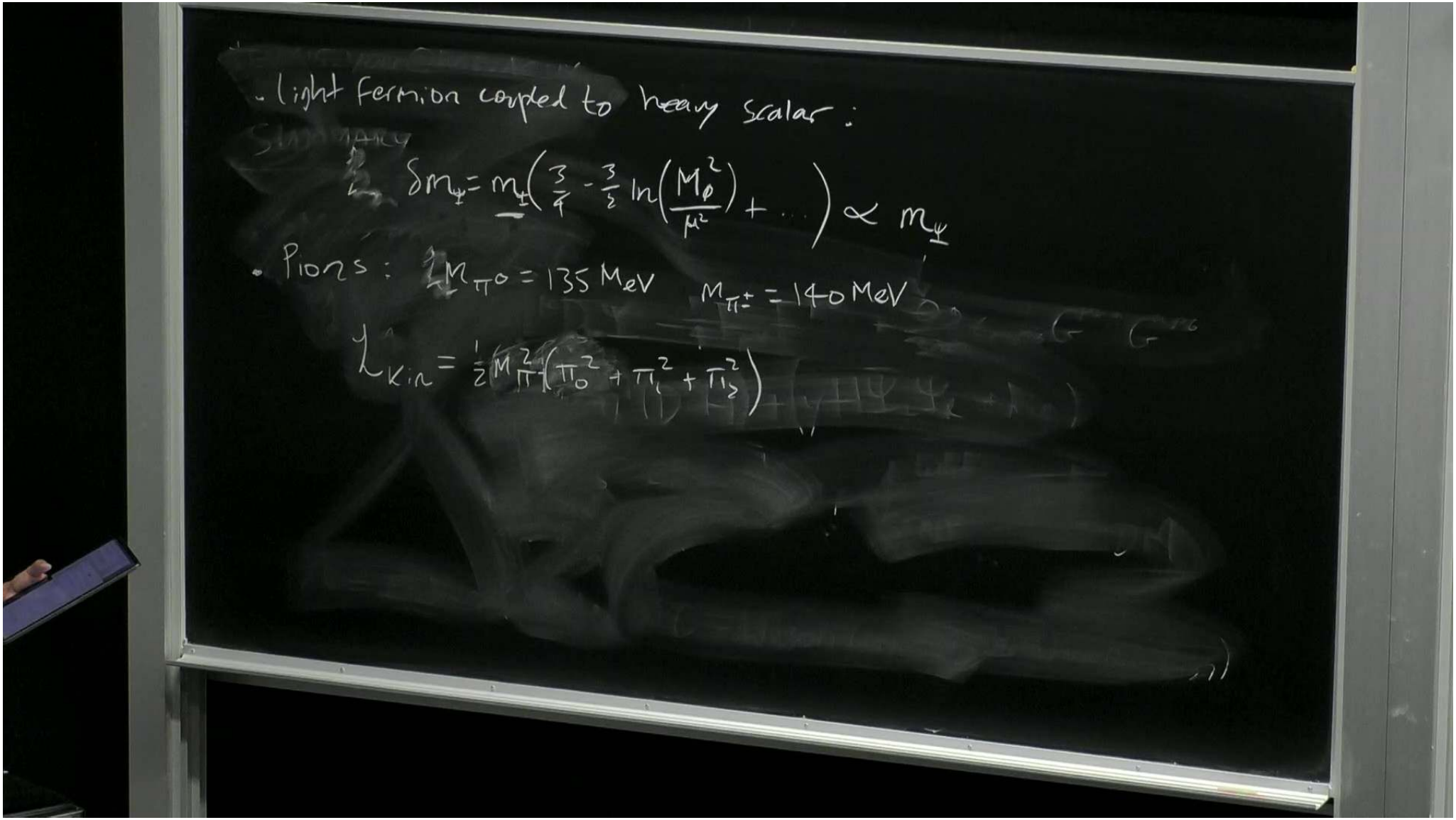


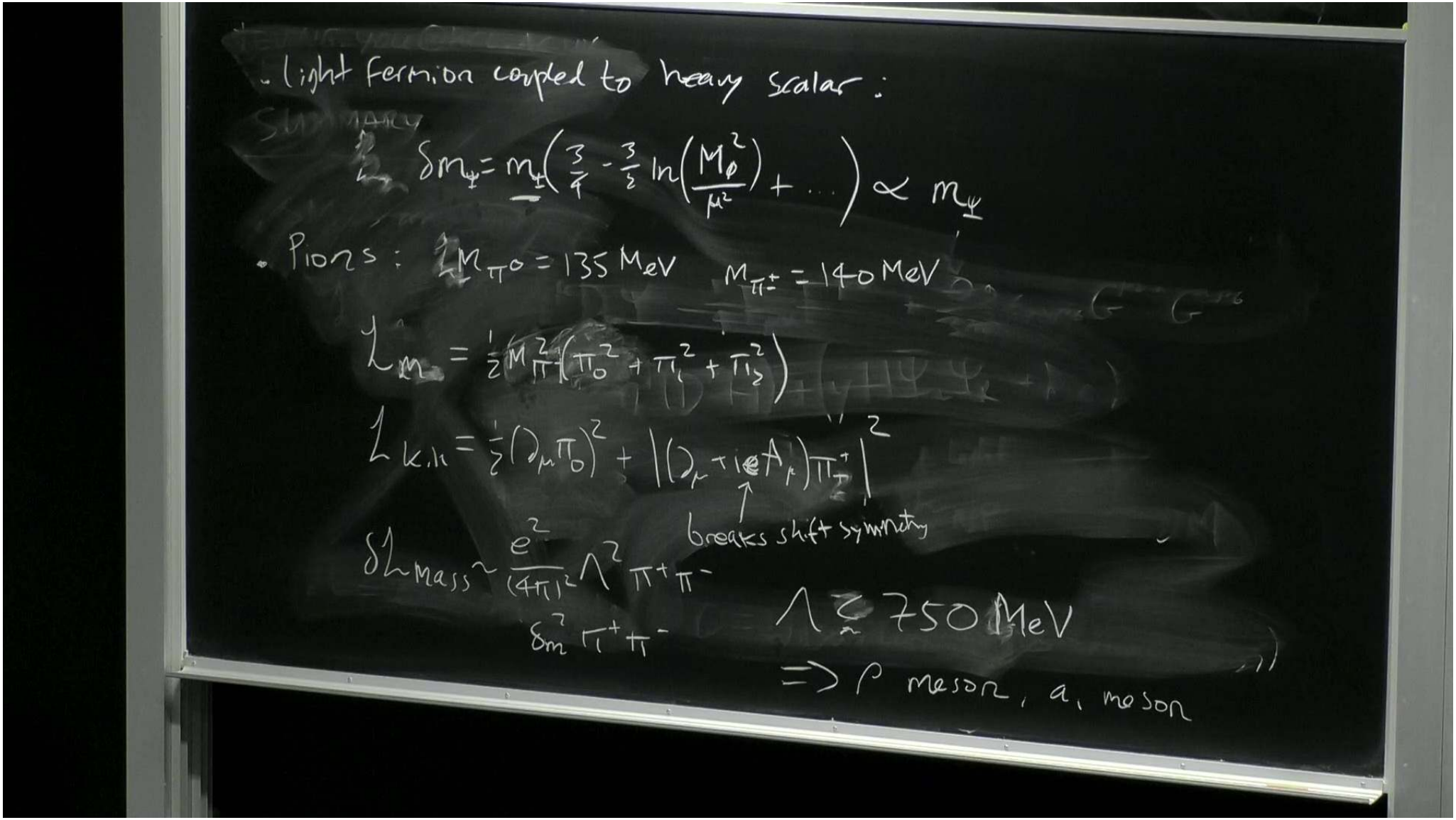
$\Lambda \sim M_\Psi$ ↑ m ↑

$$\mathcal{L}^{UV} = i\bar{\Psi}\gamma^\mu\partial_\mu\Psi - M_\Psi\bar{\Psi}\Psi + \tfrac{1}{2}(\partial_\mu\phi)^2 - \tfrac{1}{2}m^2\phi^2 - y\bar{\Psi}\Psi\phi$$

$$\mathcal{L}_{EFT} = -\frac{1}{2}\left[m^2 + \frac{y^2}{4\pi^2}\left(1 - 3\log\frac{M_\Psi^2}{\pi^2}\right)M_\Psi^2\right]\phi^2$$

- 't-Hooft: "technical" naturalness: if a symmetry is restored when a parameter goes to zero then it is technically natural for that parameter to be small.


• light fermion coupled to heavy scalar:
$\delta m_\psi = m_\psi\left(\frac{3}{4} - \frac{3}{2}\ln\left(\frac{M_\phi^2}{\mu^2}\right) + \dots\right) \propto m_\psi$
• Pions: $M_{\pi^0} = 135\,\text{MeV}$ $M_{\pi^\pm} = 140\,\text{MeV}$
$\mathcal{L}_{kin} = \frac{1}{2}M_\pi^2\left(\pi_0^2 + \pi_1^2 + \pi_2^2\right)$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Pions: $M_{\pi^0} = 135\,\text{MeV}$ $M_{\pi^\pm} = 140\,\text{MeV}$
$\mathcal{L}_m = \frac{1}{2}M_\pi^2(\pi_0^2 + \pi_1^2 + \pi_2^2)$
$\mathcal{L}_{kin} = \frac{1}{2}(\partial_\mu\pi_0)^2 + |(\partial_\mu + ieA_\mu)\pi_2^+|^2$
breaks shift symmetry
$\delta\mathcal{L}_{mass} \sim \frac{e^2}{(4\pi)^2}\Lambda^2\,\pi^+\pi^-$
$\delta m^2\,\pi^+\pi^-$
$\Lambda \lesssim 750\,\text{MeV}$
$\Rightarrow \rho$ meson, a_1 meson